

Quark-nova compact remnants: Observational signatures in astronomical data and implications to compact stars

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Quark-novae leave behind quark stars with a surrounding metal-rich fall-back (ring-like) material. These compact remnants have high magnetic fields and are misconstrued as magnetars; however, several observational features allow us to distinguish a quark star (left behind by a quark-nova) from a neutron star with high magnetic field. In our model, bursting activity is expected from intermittent accretion events from the surrounding fall-back debris leading to X-ray bursts (in the case of a Keplerian ring) or gamma ray bursts (in the case of a co-rotating shell). The details of the spectra are described by a constant background X-ray luminosity from the expulsion of magnetic flux tubes which will be temporarily buried by bursting events caused by accretion of material onto the quark star surface. These accretion events emit high energy photons and heat up the quark star and surrounding debris leading to hot spots which may be observable as distinct blackbodies. Additionally, we explain observed spectral line features as atomic lines from r-process material and explain an observed anti-glitch in an AXP as the transfer of angular momentum from a surrounding Keplerian disk to the quark star.

Keywords: dense mater; magnetic fields; stars: magnetars; stars: neutron; X-rays: bursts; X-rays: stars

1. Introduction

Analogous to a core-collapse supernova, a quark-nova is the explosion of a neutron star which leaves behind a quark star. In the quark-nova model, the compact remnant left behind is a quark star composed of deconfined up, down and strange quarks in a color-superconducting phase. The quark star has many observable similarities to a neutron star and is especially likely to be mislabelled as a magnetar due to its intrinsically high magnetic field at birth. As a compact remnant, the quark star distinguishes itself from other compact objects by the properties of its constituent quark matter and its formation mechanism which ejects an r-process rich crust which leaves behind metal rich debris. These properties cause the quark-star to emit in X-ray and gamma ray and causes intermittent bursting phases which make it an excellent candidate for not just magnetars, but also soft gamma repeaters (SGRs), anomalous X-ray pulsars (AXPs) rotating radio transients (RRATs) and X-ray dim isolated neutron stars (XDINs).

2. Quark-novae

Quark-novae convert the parent neutron star into a quark star.¹ The explosive event ejects an outer layer of the neutron star crust ($\sim 10^{-3}M_{\odot}$) and leaves behind a quark star. The relativistic ejecta ($\gamma \geq 10$) is initially an extremely dense (10^{14} g/cc)

and neutron rich environment ideal for formation of heavy elements through the r-process (see Refs. 2, 3 and 4 for more details). This ejecta may be visible following the quark-nova either by interaction with surrounding material as a super-luminous or double-humped supernova,^{5,6} or by the decay of unstable r-process isotopes as a fast radio burst.⁷ Additional observational evidence for this r-process rich material may exist in the form of gravitationally bound fall-back material surrounding the quark-star. This fall-back material can either form a co-rotating shell, or a Keplerian disk depending on the period of the parent neutron star. The large amount of material ($10^{-7}M_{\odot}$) in these rotating structures provides additional emission spectra through both black-body radiation and accretion onto the bare quark star.

2.1. Quark-nova compact remnant: aligned rotator

The quark star remnant of the quark-nova is left in a colour-superconducting phase and the magnetic field of the quark star becomes quantized and constrained to vortices in an Abrikosov lattice. This results a compact object whose surface magnetic field becomes much stronger and is forced into alignment with its rotation through the Meissner effect.⁸ As the star ages, spin-down causes magnetic field vortex expulsion which leads to heating of the quark star surface and X-ray emission from magnetic reconnection events.⁹ This ultimately leads to the slow decay of the quark star magnetic field and produces a compact body which cannot exhibit the light-house pulsations of a neutron star, but will instead appear in X-ray. The X-ray emission will decay over time and is consistent with observations of XDINS and SGRs (see Fig. 2 in 10). The luminosity of the vortex band is given by:

$$L_X \approx 2.01 \times 10^{35} \eta_X \dot{P}_{-11}^2 \text{ ergs}^{-1} \quad (1)$$

where η_X is an efficiency factor for conversion of magnetic energy to radiation.¹

3. Quark-nova connection to AXPs and SGRs

During the quark-nova a small fraction ($\sim 10^{-7}M_{\odot}$) of the ejecta will remain gravitationally bound. Depending of the spin of the neutron star progenitor, this debris will form into either a co-rotating shell ($P > 10$ ms) or a Keplerian disk ($P \sim 5$ ms). As with the escaped ejecta, this material will be rich in r-process ($Z > 26$) elements. This debris surrounding the quark star provides an additional source of material which may radiate or interact with the quark star. In both cases, it may be possible to identify the presence of two distinct blackbodies (where one is the quark star and the second is the surrounding debris) at two different temperatures.

3.1. Co-rotating debris: SGRs

For slow rotating neutron star progenitors, the fall-back material will settle into a co-rotating degenerate shell surrounding the quark-star,¹¹ where the surrounding shell is supported by the quark star's magnetic field pressure. Because of this,

there is a critical latitude at which material near the poles does not have sufficient magnetic support to overcome the quark star's gravitational field. As the star ages, magnetic field decay, contraction of the co-rotating shell, hydrodynamic instabilities and changes in the stability point cause accretion of material from the shell onto the quark star's surface. These accretion phases cause sudden shearing off of material from the co-rotating shell and results in the release gamma rays as the accreted matter from the shell impact onto the surface of the quark star. During quiescent phases, these SGRs will be emitting in X-ray from the magnetic field decay as described by Eq. 1.

3.2. *Keplerian debris: AXPs*

Rapidly rotating neutron stars will instead form a degenerate Keplerian disk surrounding the quark-star.¹² The magnetic field of the quark star slowly penetrates through the degenerate ring and threads the inner ring. This penetration front (Bohm Front) proceeds through the degenerate layers of the ring and forces co-rotation of the inner threaded portion of the now non-degenerate inner section of the debris. At the front, before complete penetration and forced co-rotation with the magnetic field, the non-degenerate material is expelled from the disk through a Kelvin-Helmoltz instability and accreted onto the quark star's surface. This leads to a stream of material from the Keplerian disk which is accreted onto the quark star creating hot-spots near the poles. Dissipation of magnetic bubbles generated at the ring during these outburst provides a source of transient radio emission which has been associated with some AXPs following bursting periods.¹³ When these accretion events happen the inner ring of the disk will be heated by radiation from the surface of the quark star. During quiescent phases, the quark star–ring system should have two emission spectra (X-ray and black body). During bursting, however, the inner portion of the ring will heat up (increasing its black body temperature) and hot spots on the quark star surface will become visible as an additional black body. Of course, as the material from the Keplerian ring is transferred onto the quark star, the star may be spun up or down depending on radial drift velocity of the accreted material which changes with the radial distance.

As the quark star and Keplerian disk age, the ring begins to spread out and eventually succumbs to gradual mass leakage. The gradual accretion from the surrounding ring provides a steady stream of matter onto the surface of the quark star leading to an accretion dominated phase.¹⁰ Now the quiescent phase of the quark star's X-ray luminosity is dominated by the accretion luminosity of hot spots on the star. As the debris is accreted the luminosity slowly decreases and, once the ring has been completely consumed, the quark star will return to the vortex band and emit primarily X-rays from the magnetic reconnection of the ever decaying magnetic field (see Fig. 2 of Ref. 10). This means that despite their differences early on, AXPs and SGRs will both eventually converge to the vortex band and eventually cease bursting activity after they have consumed the entirety of the fall-back material

from the original quark-nova.

4. Quark-nova bursting signatures

When a quark-star enters into its bursting phases, it will energize the surrounding material. This transfer of energy heats up the surrounding debris and may cause atomic spectral line emission or cause changes to the rotational mode of the Keplerian disk.

4.1. Atomic 13 keV lines

Spectral line features around 13 keV have been detected in several different AXPs. The common explanation for these spectral lines has been a cyclotron emission in the atmosphere of a magnetar. This explanation has been strained by the repeated observations of several different line features at the same frequency in different AXPs. Additionally, the magnetic field strength inferred (assuming proton cyclotron emission) is inconsistent with the characteristic magnetic field strength (inferred from period and spin-down measurements). Instead, we suggest that this observed spectral feature may be an atomic transition line. Since the fall-back material from the quark-nova ejecta is so neutron rich, the degenerate ring or co-rotating shell is composed of r-process elements. Normally, these isotopes are too dim to detect spectroscopically; however, during bursting phases these elements are heated up and become spectroscopically visible. The frequencies at which these elements emit is then completely independent of magnetic field strength and would be at identical between frequencies for all AXPs. Analysis of the atomic line strengths of elements suggests that this is a 13 keV emission feature from a strontium or rubidium line.^{14,15} The number of observed 13 keV lines makes it unlikely that this is a proton cyclotron line since that would require the magnetic fields to be the same in each magnetar. As more of these spectral lines are observed, it may begin to statistically rule out magnetars altogether and atomic line spectra provides a natural explanation for a common 13 keV line to be present in all AXPs.

4.2. Anti-glitches

The observation of an anti-glitches associated with AXP 1E2259+586 proved to be a puzzling phenomena. In our model, AXP bursts are generated by accretion of material from a surrounding disk.¹⁶ These bursting phases re-energize the surrounding material and may cause retrograde motion in a surrounding Keplerian disk. For this particular AXP, the hypothesis is that the observed burst in 2002 caused a reversal in the inner ring of the Keplerian disk. Then, in 2012, material from the ring was accreted causing spin-down due to the transfer of angular momentum from the now retrograde inner ring. As a result, further bursts from the same AXP may cause further anti-glitches if the 2002 burst was energetic enough to reverse several layers

of the surrounding inner ring. Coincident observation of atomic r-process spectral features would further strengthen this hypothesis.

5. Conclusion

The quark-nova model proposes that quark stars are the compact remnant left behind following the explosion of a neutron star. The explosion process leaves behind debris which form a gravitationally bound disk or ring around the quark star. This quark star–debris system emits in X-ray and is subject to several bursting phases over the course of its lifetime leading to either SGRs, or AXPs. The X-ray luminosity generated by vortex expulsion is consistent with observations of SGRs and AXPs and suggests a common ancestry for both. This picture is similar to magnetar models for AXPs and SGRs, but can be distinguished by detailed analysis of the observed spectra. Based on our model we expect that future bursting events should be associated with both low and high B magnetars and may be coincident with anti-glitches and r-process atomic spectral lines.

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